RXTE X-ray Monitoring of the Supermassive Star Eta Carinae: Colliding Wind Emission in a Pre-Hypernova Candidate Binary?

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Abstract. *ROSAT*, *ASCA*, *RXTE* and now *Chandra* X-ray observations of the supermassive star η Carinae obtained over the past 7 years chronicle the inordinate variability of the high-energy emission. The most important characteristics are these: 1) the hard X-ray "low state" evidently recurs with a period consistent with the "Damineli Cycle" of 5.5 years; 2) the X-ray emission exhibits "flares" which occur quasi-periodically; 3) the overall X-ray brightness in the current "cycle" is brighter than at the same phase in the last cycle; 4) the hard, variable "core" source is apparently resolvable at lower energies but unresolvable at energies above $\sim$ 4 keV. The X-ray data appear consistent with a model of X-ray generation via colliding winds in a massive binary system coupled with dust scattering, though the "flaring" activity probably requires that the wind from at least one of the stars is azimuthally structured. It is difficult to account for all the X-ray properties by activity in a single star.

INTRODUCTION

Massive stars are key astronomical objects due to their important role in cosmic chemical enrichment and galactic evolution. They mark the end of their stellar lives as supernovae whose peak luminosity can equal the entire radiant output of a galaxy of a trillion stars. The extreme members of this class might produce "hypernovae" [1], cataclysms hundreds of times more energetic still, and a postulated source of gamma ray bursts. Such extraordinary explosions require stellar precursors of unusually large mass, and so should be rare. The Milky Way contains at least one possible member of this putative class of hypernova progenitors, the massive, luminous, and relatively nearby star, η Carinae.

Recent observations of periodic variations in some emission lines of the η Carinae spectrum suggest [2] that the star has a companion in a long-period ($P = 5.52$ years) eccentric ($e > 0.6$) orbit. Such a companion potentially provides a crucial key to understanding η Carinae. At the very least, the presence of a companion offers the most direct measure of the current mass of η Carinae (and so would provide an important empirical point for the mass-luminosity relation in the upper HR diagram). In addition, the companion can possibly interact with η Carinae and so change the course of the evolution of the star. In principle the companion's presence could help resolve some outstanding mysteries (such as the nature of the large eruptions which took place during the 1840's and 1890's), especially if tidally-induced mass transfer or other interaction effects are important.

Unfortunately, the spectrum of the star and its close neighborhood is contaminated by emission lines which are formed in thick clouds of circumstellar ejecta, so the interpretation of the spectral variations as a signature of binarity is by no means clear. Periodic mass ejections from a single star have also been suggested as a possible explanation of the observed emission-line changes [3]. Clearly, to understand the present and future state of the star, we need to determine whether η Carinae has a companion.

PERIODIC X-RAY EMISSION

A direct consequence of the presence of a companion is that the wind from η Carinae should collide with the wind or surface of this companion. This collision would produce substantial amounts of hot, shocked gas [4,5] and observable X-ray emission. These "colliding wind" X-rays would be characteristically hard ($kT \sim$ a few keV), absorbed ($N_H >$ few $\times 10^{22}$), and, most importantly, the colliding wind X-rays would vary with the orbital cycle. Thus the X-ray emission from η Carinae provides important evidence to prove or disprove the binary hypothesis. Since the optical spectrum of the star is so contaminated with circumstellar emission, X-ray variability could be the *best* way to determine the orbital properties if the star indeed has a companion.

To characterize the variability of the X-ray spectrum fromη Carinae in detail, we have used the Proportional Counter Array (PCA) on the Rossi X-ray Timing Explorer (*RXTE*) and the *ASCA* X-ray observatory to monitor the 2-10 keV X-ray emission from the source.

RESULTS OF THE X-RAY MONITORING

A preliminary analysis of the *RXTE* data through mid-1997 [6] already noted an overall increase in the mean *RXTE* X-ray flux which accelerated after January 1997, with unexpected periodic "flares" occurring every 84.8 days. Our more recent data show that the X-ray variability through January 1998 proved to be more extreme than previously suspected.

The most fundamental result of this monitoring campaign is that the X-ray "low state" first observed in 1992.5 [7] did indeed recur near 1998.0, i.e. after the "Damineli cycle" of 5.5 years. Figure 1 shows the X-ray image of η Car in the 1992–1999 interval. The point-like core at the center of the image is invisible during the "low states" in 1992.5 and 1998.0, but clearly seen (by both *ROSAT* and *Chandra*) outside the "low state".

The observed X-ray flux in the 2–10 keV energy band reached its maximum ($F_{x,obs} \approx 2 \times 10^{-10}$ ergs s^{-1} cm^{-2}) on 9 November 1997, and plummeted thereafter. In only a month's time the observed X-ray flux dropped by 2 orders of magnitude ($F_{x,obs} \approx 2 \times 10^{-12}$ ergs s^{-1} cm^{-2}) and the source became nearly undetectable to the PCA. The star remained faint for more than 2 months before the X-ray emission began to recover substantially.

As discussed in [8], the X-ray variability mimics the expected variations which would be seen if the X-rays are produced by wind-wind collisions in a binary system, thus supporting the idea that η Car is indeed a binary system. However there is a significant discrepancy in the observed low-state spectrum, in which the observed

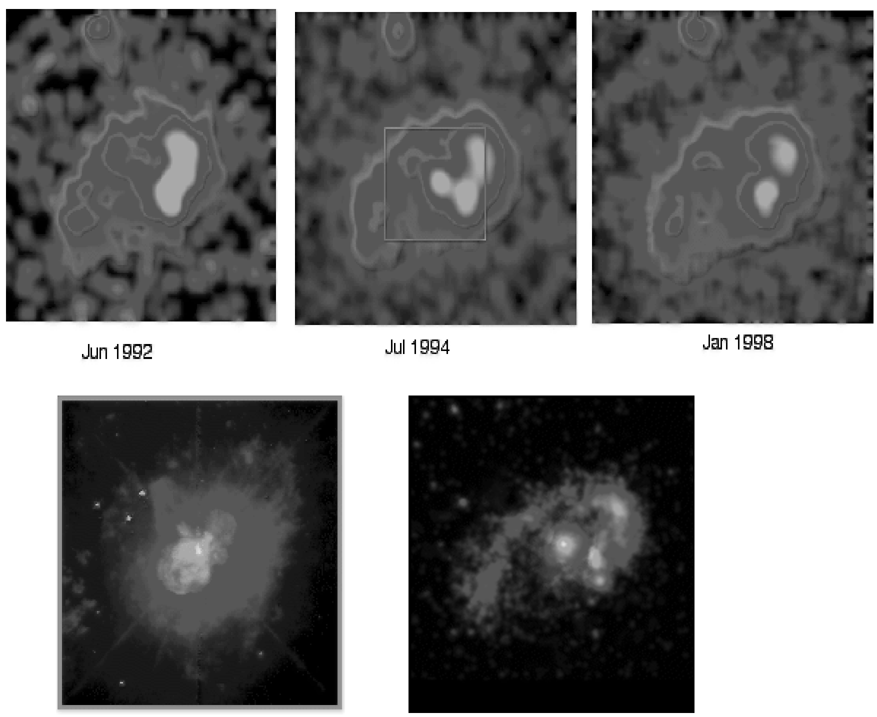

FIGURE 1. High-Resolution images showing the variability of the central source at the center of the η Car image at 4 epochs: top left, *ROSAT* HRI Jun 1992 (during the last "low state"); top middle, *ROSAT* HRI Jul 1994 (the "normal" state); top right, *ROSAT* HRI Jan 1998 (the most recent "low state"). The image on the lower right is the *Chandra*/ACIS observation from Sep 1999 (courtesy *Chandra* X-ray Observatory Center). The HST WFPC2 image is lower left.

N_H is much lower ($\approx 5 \times 10^{22}$ cm^{-2}) than model predictions ($\geq 10^{24}$ cm^{-2} at the time of minimum flux). The recent *Chandra* observation may solve this discrepancy, since a preliminary analysis of the ACIS data suggests that significant amounts of flux near 2 keV are produced in an extended region around the core (and possibly in the "shell" as well). If so then this non-varying emission would contaminate the *RXTE* and *ASCA* spectra during the low-flux state and cause the spectral analysis to severely underestimate the actual N_H to the core.

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